

SMALL DWARF GALAXIES WITHIN LARGER DWARFS: WHY SOME ARE LUMINOUS WHILE MOST GO DARK

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ABSTRACT

We consider the possibility that the Magellanic Clouds were the largest members of a group of dwarf galaxies that entered the Milky Way (MW) halo at late times. Seven of the eleven brightest satellites of the MW may have been part of this system. The proximity of some dwarfs to the plane of the orbit of the Large Magellanic Cloud (LMC) has been used to argue that they formed from tidal debris from the LMC and Small Magellanic Cloud (SMC). Instead, they may owe to the tidal breakup of the Magellanic group. This can explain the association of many of the dwarf galaxies in the Local Group with the LMC system. It provides a mechanism for lighting up dwarf galaxies and reproduces the bright end of the cumulative circular velocity distribution of the satellites in the MW without invoking a stripping scenario for the subhalos to match the satellite distribution expected according to CDM theory. Finally, our model predicts that other isolated dwarfs will be found to have companions. Evidence for this prediction is provided by nearby, recently discovered dwarf associations.

Subject headings: cosmology: observations — dark matter — galaxies: clusters: general — galaxies: formation

Online material: color figure

1. INTRODUCTION

Dwarf galaxies in the Local Group are puzzling for several reasons. Some of them appear to be orbiting in roughly the same plane, and observations suggest that this plane contains the Magellanic Clouds along with some dwarf spheroidals. This association of dwarfs with the plane of the orbit of the LMC has been used to argue that dwarf galaxies formed from tidal debris from the LMC and SMC (Kroupa et al. 2005). However, this suggestion is challenged by the large dark matter content of the dwarf galaxies, which is contrary to what is expected if they are tidal debris (e.g., Barnes & Hernquist 1992).

Another interesting aspect of the Local Group dwarf galaxies is that simulations with only dark matter predict that the subhalos should outnumber the modest population of observed, luminous dwarfs orbiting the MW and M31 by a factor of 10–100 (Kauffman et al. 1993; Klypin et al. 1999; Moore et al. 1999). This discrepancy between the predicted and observed numbers of dwarf galaxies has become known as the *missing dwarf problem*. The population of ultrafaint dwarfs around the MW and M31 found in the Sloan Digital Sky Survey (Willman et al. 2005a, 2005b; Zucker et al. 2006) has increased the number of observed satellites by a factor of 2. It is unclear, however, whether this can reconcile theory and observation (Simon & Geha 2007).

Cosmological solutions to the missing dwarf problem include modifying the power spectrum on small scales (e.g., Zentner & Bullock 2003 and references therein) and changing the nature of the dark matter, by assuming a warm dark matter particle (e.g., Colin et al. 2000; Avila-Reese et al. 2001) or by invoking decay from a nonrelativistic particle (Strigari et al. 2007). Proposed astrophysical solutions typically appeal to feedback effects associated with stellar evolution or heating from UV radiation to inhibit the formation of dwarfs by suppressing star formation in low-mass halos (e.g., Bullock et al. 2000; Somerville 2002; Benson et al. 2002).

An alternate scenario has been proposed by Kravtsov et al. (2004) in which the dwarf spheroidals we observe today were

once much more massive objects that have been reduced to their present mass by tidal stripping. On larger scales, the substructure function inside clusters and groups is not well-determined and little is known about the behavior of substructure over a range of masses (D'Onghia & Lake 2004). Data show a clear deficiency of substructure in systems of $\sim 10^{12} M_{\odot}$, characteristic of the mass of the MW, and mixed results for systems with larger masses of a few $\times 10^{13} M_{\odot}$ (e.g., D'Onghia et al. 2008).

In this Letter, we propose a scenario in which the Magellanic Clouds and seven of the eleven dwarf galaxies around the MW were accreted as a group of dwarfs which was disrupted in the halo of our Galaxy. This possibility is motivated by observations described in the next section which indicate that dwarfs are often found in associations and theoretically by numerical simulations (e.g., Li & Helmi 2008) which show that subhalos are often accreted in small groups.

If the LMC, SMC, and some dwarfs fell into the Milky Way in a group rather than individually, they are more likely to end up orbiting in roughly the same plane than according to earlier models. For example, Libeskind et al. (2005) determined that subhalos are anisotropically distributed in cosmological CDM simulations and that the most massive satellites tend to be aligned with filaments. Zentner et al. (2005) suggested that the accretion of satellites along filaments in a triaxial potential leads to an anisotropic distribution of satellites. Systems anisotropically distributed falling into the Galactic halo are, however, unlikely to lie in a plane consistent with the orbital and spatial distribution of the MW satellites (see, e.g., Metz et al. 2008). As we argue further below, our scenario also provides a new mechanism for lighting up the dSphs in the Local Group that naturally reproduces the bright end of the cumulative circular velocity distribution of the satellite dwarf galaxies in the MW.

1.1. Evidence for a Disrupted Magellanic Group

It has been recognized for many years that many dwarf galaxies may be associated with the Magellanic Clouds (Lynden-Bell 1976; Fusi Pecci et al. 1995; Kroupa et al. 2005). The number of dwarfs possibly related to the Magellanic plane group (Kunkel & Demers 1976) has increased with time and

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TABLE 1
NEARBY DWARF GALAXY ASSOCIATIONS

Name	v_{par} (km s ⁻¹)	v_{min} (km s ⁻¹)	N_{obs}
NGC 1313	131	26	2
NGC 4214	88	26	6
NGC 3109	75	14	3
NGC 55	104	21	5
NGC 784	77	23	4
ESO 154-023	70	61	2
DDO 190	67	43	3
DDO 47	44	29	3

now includes the following *candidates*: Sagittarius, Ursa Minor, Draco, Sextans, and Leo II. Of the dwarfs known before the recent flurry of discoveries, 7 out of 10 within ~ 200 kpc might well be connected with the Magellanic Clouds. The remaining three—Fornax, Sculptor, and Carina—have been proposed to be part of a second grouping (Lynden-Bell 1982). The distribution of distant halo globular clusters has been used to reinforce the existence of both groups (Kunkel 1979; Majewski 1994).

The LMC and SMC have long been viewed as a pair owing to their spatial proximity. They have been modeled as either being currently bound or having only become unbound on a very recent perigalacticon passage (Lin & Lynden-Bell 1982). The “Magellanic Bridge” of neutral hydrogen supports their being physically connected (Kerr et al. 1954). New distance and proper motion measurements suggest that the clouds are traveling together but have become unbound. The LMC is at a distance of ≈ 49 kpc from the Galactic center and has a tangential velocity of ~ 345 km s⁻¹ in Galactic coordinates (Kallivayalil et al. 2006b). The proper motion of the SMC implies a velocity relative to the LMC of ~ 80 km s⁻¹ at a separation of 23 kpc (Kallivayalil et al. 2006a). Given the circular velocity of the LMC (76 km s⁻¹) and the group’s large initial virial radius (~ 75 kpc), the relative velocity of the SMC appears modest. However, the current tidal radius of the LMC group is only ~ 10 kpc, so the SMC is likely unbound, although it can travel with the LMC for a long time owing to its relative retrograde motion and the larger effective tidal radius for such an orbit (Read et al. 2006). Simply put, the SMC travels in an epicycle around the LMC so that they remain near for several orbits after tidal breakup (Kallivayalil et al. 2006a).

The orbits of the pair depend on the total mass of the MW. For a traditional mass model with a total virial mass of $2 \times 10^{12} M_{\odot}$, the orbit of the clouds currently has a rough peri- and apogalacticon of 50 and 150 kpc (Kallivayalil et al. 2006a) respectively, with an implied apogalacticon 10 Gyr ago of ~ 250 kpc and little evolution in the perigalacticon, if dynamical friction is included. In this picture, the Magellanic group likely entered the MW halo at a redshift between 2 and 3 or even at later times. Recent analysis by Besla et al. (2007) using a broader range of halo models motivated by cosmological simulations admits the possibility that the LMC has just fallen into the MW, is moving at close to the escape velocity at its location, and is approaching its orbital pericenter for the first time.

Here, we examine the possibility that the LMC, SMC, and those dwarfs whose orbits are similar to those of the Magellanic Clouds were all originally part of a group that was accreted by the Milky Way and tidally disrupted. This “LMC group” was dominated by the LMC and had a parent halo circular velocity of 75 km s⁻¹ (Kim et al. 1998) with its brightest satellite, the SMC, having a rotation velocity of 60 km s⁻¹ as estimated from its H I distribution (Stanimirovic et al. 2004).

There is considerable evidence for tidal debris from the LMC group, supporting the proposal that it was tidally disrupted. For example, microlensing studies of the Magellanic Clouds find more self lensing than anticipated (Alcock et al. 1997; Palanque-Delabrouille et al. 1998). This was interpreted as self-lensing by the Magellanic Clouds, although inconsistent with the structure of the LMC disk (Gyuk et al. 2000). Zaritsky & Lin (1997) find direct evidence for an *intervening* stellar population which may comprise tidal debris.

An interesting characteristic of the LMC group is that its orbital angular momentum is comparable to the entire MW, but is oriented at 90° relative to the disk plane. The specific angular momentum of an exponential disk rotating with constant velocity $v_{\text{circ}} = 220$ km s⁻¹ and scale length $r_s = 2.8$ kpc is $2v_{\text{circ}}r_s \sim 560$ kpc km s⁻¹. The specific angular momentum of the LMC is its galactocentric distance times its transverse velocity relative to the galactic center. From Kallivayalil et al. (2006a), this is 1.8×10^4 kpc km s⁻¹. Hence, the LMC group has a specific angular momentum that is roughly 20 times greater than the disk of the MW. The mass of the LMC group was approximately ~ 0.04 the mass of the MW. If we assume that the entire halo of the galaxy has the same specific angular momentum as the disk, the total angular momentum of the LMC group is greater than the product of the entire mass of the MW system times the specific angular momentum of the disk (e.g., Fich & Tremaine 1991; Besla et al. 2007). This tilts the angular momentum vector of the MW system by $\sim 45^\circ$ and may have significant implications for comparing cosmological simulations of angular momentum to present-day galaxies (see, e.g., Navarro et al. 2004).

2. EVIDENCE FOR ASSOCIATIONS OF NEARBY DWARF GROUPS

In addition to the expectation that abundant populations of satellites should orbit large galaxies, CDM theory predicts that many dwarf galaxies exist in the field. Numerical simulations indicate that the mass function of subhalos should be nearly independent of the mass of the parent halo (Moore et al. 1999). Thus, groups of dwarf galaxies are a natural outcome of CDM models on smaller mass scales. However, like low-mass satellites, these systems are difficult to observe.

Tully (2006) discovered a number of associations of dwarf galaxies within 5 Mpc of the MW. These groups have properties expected for bound systems with $(1-10) \times 10^{11} M_{\odot}$, but are not dense enough to have virialized, and have little gas and few stars. Of the eight associations compiled by Tully (2006), there are only three for which the two brightest galaxies differ by at least 1.5 mag: NGC 3109, NGC 1313, and NGC 4214. In the other five, the two brightest galaxies are certain to merge if the associations collapse and virialize. We list the properties of the eight associations of dwarfs in Table 1. The other five low-luminosity dwarf galaxies with associated companions listed in Table 1 are NGC 55, NGC 784, ESO 154-0123, DDO 190, and DDO 47.

For each association, the largest dwarf galaxy is considered. The columns in Table 1 list the name of the nearby low-luminosity galaxies with associated companions, the circular velocity of the largest dwarf galaxy in each association v_{par} (which is assumed to be the parent halo circular velocity), the circular velocity of the smallest dwarf galaxy in the association, and the minimum number of observed members N_{obs} . Magnitudes of member galaxies are converted to circular velocity assuming a Tully-Fisher relation in the *B* band. Note that of the three associations with the two brightest galaxies differing by at least 1.5 mag, NGC 3109 has a rotation velocity roughly equal to

the LMC, while NGC 1313 and NGC 4214 are larger with rotation velocities of 88 and 131 km s⁻¹, respectively.

For our analysis, we compare the cumulative circular velocity distribution of each dwarf which is part of the association with the one inferred for the MW and for a model where the Magellanic group has been disrupted into the MW. The MW data we employ to construct the cumulative circular velocity distribution of dwarf galaxies includes the newest dwarfs with a minimum $\sigma = 3.3$ km s⁻¹ and a correction for incomplete sky coverage (Simon & Geha 2007).

Figure 1 (*left panel*) shows the cumulative circular velocity distribution inferred for the dwarfs inside the eight associations discovered by Tully (2006), the Magellanic group disrupted in the Galactic halo, and the MW satellite galaxies (Simon & Geha 2007). Figure 1 implies that the nearby associations of dwarfs have a similar cumulative circular velocity distribution to the MW, suggesting that such associations may be the progenitors of the brightest dwarf satellites in the MW. Thus, if these associations of dwarfs are accreted into larger galaxies, they can populate the bright end of the cumulative circular velocity distribution of satellites. In order to match the cumulative satellite distribution expected in CDM models, Kravtsov et al. (2004) suggested that the dwarf spheroidals we observe today were once much more massive objects that have been reduced to their present mass by tidal stripping. In this way, the predicted high mass end of the cumulative subhalo function can be matched. Figure 1 indicates that if the LMC group fell into the MW, the bright end of the satellite galaxy distribution is reproduced.

3. LMC GROUP IN A COSMOLOGICAL SIMULATION

To investigate the plausibility of our model, we examined a catalog of high-resolution galaxies in a cosmologically simulated volume to identify an analog to an LMC group falling late into a MW galaxy. The simulation we employed was performed in a box 90 Mpc (comoving) on a side with 300³ particles, using the tree code PKDGRAV (Stadel 2001). The cosmological parameters were chosen to match the WMAP3 constraints (Spergel et al. 2007): a present-day matter density, $\Omega_0 = 0.238$; a cosmological constant, $\Omega_\Lambda = 0.762$; a Hubble parameter $h = 0.73$ ($H_0 = 100 h$ km s⁻¹ Mpc⁻¹); a mass perturbation spectrum with spectral index, $n = 0.951$; and a normalization, $\sigma_8 = 0.75$.

In this volume, we located a loose group with properties similar to the Local Group and which had an LMC type object being accreted by a MW size halo at a relatively low redshift. This loose group was selected and resimulated at higher resolution using GRAFIC 2 (Bertschinger 2001). There were almost 6 million particles inside the high-resolution region. The subhalos at $z = 0$ were identified using SKID (Stadel 2001).

Figure 2 (Plate 1) shows the group of dwarfs (at the bottom the figure) falling into the MW halo at $z = 1.12$. The object that we refer to as the MW has a peak circular velocity of 206 km s⁻¹. Within the virial radius of the simulated MW, there are a total of 70 satellites with circular velocities greater than 10 km s⁻¹. There are 23 surviving satellites of the simulated Magellanic group with 13 of them within the virial radius of the larger galaxy and 10 of them outside.

We conjecture that dwarf galaxies form in two extreme situations. In our model, dwarf galaxies accreted in LMC-like groups will be luminous, whereas if they are not accreted in groups, they will be dark, owing to the nature of the gas physics. When gas is blown out of a subhalo it eventually thermalizes to the virial temperature of the parent halo, which is $(2-5) \times$

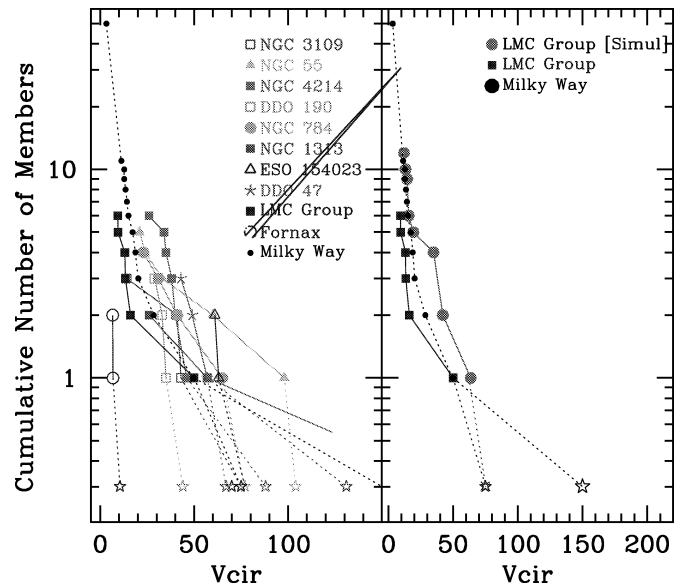


FIG. 1.—Cumulative circular velocity distribution of the satellites of the LMC group as compared to the nearby dwarf associations (*left panel*) and to the simulated LMC group in a Λ CDM model (*right panel*). [See the electronic edition of the *Journal* for a color version of this figure.]

10⁶ K for bright galaxies such as the MW. At this temperature, the cooling times are long enough that there can be a considerable reservoir of hot gas and a subhalo with a velocity scale of 10–30 km s⁻¹ will not reaccrete any gas, and it will be dark. However, in a small parent halo like the LMC, the virial temperature is only 2×10^5 K. This is at the peak of the cooling curve and the gas can therefore cool rapidly to 10⁴ K. In a group with this virial temperature, it is not possible to maintain a gaseous halo capable of stripping a subhalo by ram pressure. The internal velocity scale of 30 km s⁻¹ in the dwarf halos might well be sufficient to reaccrete some of this gas and such objects will become luminous dwarf galaxies. (Note that simulations by Keres et al. [2005] and analytical arguments [Birnboim & Dekel 2003] show that gas in halos the size of the LMC will never be heated to the virial temperature, but will instead be accreted in cold filaments of 10⁴ K. Indeed, this might be an additional mechanism for satellites to reaccrete the gas.)

We display in Figure 1 (*right panel*) the cumulative peak circular velocity distribution of the satellites contributed by the simulated infalling group of dwarfs measured at $z = 0$ within the virial radius of the MW. This is compared to the corresponding quantity for dwarfs (*filled squared symbols*) in the MW which may have been part of an accreted group: LMC, SMC, Sagittarius, Ursa Minor, Draco, Sextans, and Leo II (Lynden-Bell 1976; Kroupa et al. 2005). In Figure 1, only satellites which are accreted as part of the disrupted LMC group are displayed, because those are the dwarf galaxies which light up in our model according to the gas behavior described above. The remainder of the satellites in the simulations which are not accreted in groups but are located at $z = 0$ within the virial radius of the MW are assumed to be dark in our scenario.

4. DISCUSSION AND CONCLUSIONS

We propose a model in which the LMC was the largest galaxy of a group of galaxies that was accreted into the MW halo. Our theory addresses a number of outstanding problems in galaxy formation, particularly those associated with dwarf

galaxies, while making clear predictions that can be tested in the near future.

Our picture can account for the apparent association of many of the dwarf galaxies in the Local Group with the LMC system. A scenario in which dwarf galaxies are accreted in groups of dwarfs can explain the planar orbital configuration populated by some dSphs in the MW. Note that planar structures are observed not only in the MW halo but the dwarfs in the halo of M31 have also been grouped into planes as might be expected if they entered in association with galaxies such as M33 (Koch & Grebel 2006). If satellites are distributed anisotropically but are accreted individually, it is unlikely they would orbit in thin planes. However, if they are accreted in groups they will eventually orbit in planar structures. Prior to infall, the LMC group had a virial radius of ~ 75 kpc and a 3D velocity dispersion of ~ 100 km s $^{-1}$. So, a thin plane would still be very unusual and a wide range of kinematics is expected for the disrupted satellites.

We find that the LMC group can naturally reproduce the bright end of the cumulative circular velocity distribution of the satellite galaxies observed in the MW supporting a “gas physics” solution to the missing satellite problem rather than one that proposes altering the initial power spectrum. The internal velocity scale of 30 km s $^{-1}$ in the dwarf halos might well be sufficient to reaccrete some of this gas leading to delayed episodes of star formation, a puzzling phenomenon seen in the Local Group dwarfs (Mateo 1998; Grebel 1997). Our model predicts that other isolated dwarfs will be found to have companions down to this mass limit. The recent discovery of Leo V (Belokurov et al. 2008), a dwarf spheroidal companion of Leo IV, and the nearby dwarf associations supports our hypothesis.

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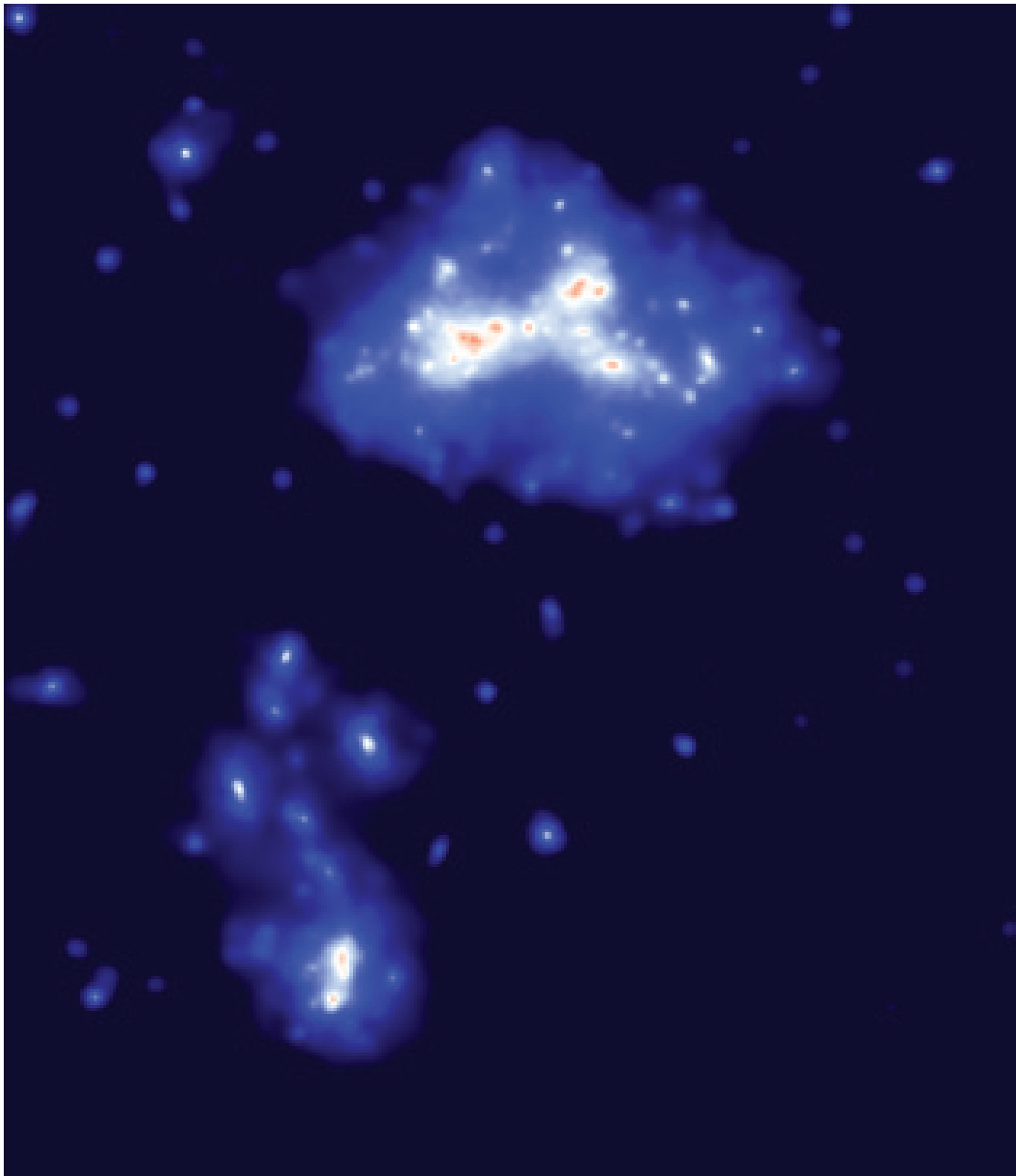


PLATE 1

FIG. 2.—Group of dwarfs dominated by the LMC (at the bottom) approaching the MW halo at $z > 1$.